



PCT/AU00/00959

REC'D 30 AUG 2000	
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WITNESS my hand this
Twenty-third day of August 2000

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ANODE ASSEMBLY COMPRISING SEPARATION OF ELECTRICAL AND MECHANICAL FUNCTIONS OF THE ASSEMBLY

Background of the Invention

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Majority of world aluminium production takes place in a Hall-Heroult Process. In this process the production of aluminium from alumina takes place in electrolytic cells or pots at a temperature of approximately 970 °C. Direct current is passed through a molten salt bath in which alumina is dissolved. The bath consists of a mixture of fluoride salts in which the main component is cryolite (Na_3AlF_6). As the electrolysis takes place in a molten salt at a high temperature in corrosive environment, the service conditions for various electrical components of the electrolysis cell are arduous.

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The typical electrolytic cell comprises a rectangular steel shell lined with refractory materials as insulation, and carbon on the hot face. The carbon blocks on the bottom of the cell contain embedded conductors for collection of current and act as the cathode. The cell holds the molten bath in which alumina is dissolved. Carbon anodes are suspended from above the cell and dip into the bath. Metallic conductors, known as anode assemblies or anode rods provide the mechanical support and carry the current to the anodes. During cell operation the bath is kept molten by the heat generated by the passage of electric current. The anodes are covered by a mixture of alumina and crushed bath to protect the anodes, particularly the connection points between the assemblies and carbon from airburn. Oxygen is released at the anodes where it reacts with carbon to produce mainly CO_2 gas and release small amounts of CO and SO_2 . The alumina is added to the bath as needed by breaking the crust. Alumina contains a small amount of moisture and trace amounts of common salt (NaCl). The reaction between moisture in the alumina, fluorides and chlorides in the molten bath releases a cocktail of gases (SO_2 , HCl and HF) which at elevated temperatures can be highly corrosive with respect to anode assemblies. The CO_2 gas released at the electrolytic face is highly oxidising with respect to consumption of carbon on the

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sides of anode and on the hot faces of the anode which are exposed to pot atmosphere below the crust and ore cover. The consumption of carbon from anode sides is completely redundant and represents an additional cost to the process.

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Conventional aluminium reduction plants require a large infrastructure, typically costing above US\$4000 per tonne of installed capacity and a large amount of electrical energy and carbon. The arduous service conditions impose expensive maintenance requirements on pots and anode assemblies. By increasing the production capacity of the existing plants and reducing the consumption of electrical energy and carbon and by reducing the need for anode assembly maintenance, a reduction of cost of aluminium production can be achieved.

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15 Summary of the Invention

The present invention is directed to a novel anode assembly construction for supporting anodes particularly adapted for use in the existing Hall-Heroult cell applications. The anode bar of the present invention increases the production capacity and power efficiency in existing cells through innovative anode assembly construction, better process heat extraction and more efficient use and conversion of raw materials. The anode assemblies, through a selection of materials and design are maintenance free and virtually process indestructible. In case of extreme process excursions and damage, the anode assemblies require specialised refurbishment or recycling of high value materials. These assemblies are designed to prevent being damaged and not for easy repair of damaged components.

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Specifically, the anode assembly of the present invention is preferably formed from a core material of high electrical and thermal conductivity such as copper or aluminium, encased in a protective sheath of high temperature structural material with similar thermal expansion properties, such as austenitic stainless steel. The sheath material provides the high temperature strength and resistance to hot corrosive gases, and

the core material, free from mechanical duties, provides for conduction and distribution of current from the assembly to the carbon and heat from the carbon to the pot atmosphere. The internal joins and electrical contact interfaces between the conductive core and outer sheath are completely protected from ingress of oxygen and other corrosive gasses by welding.

The lower part of the assembly, which is in intimate contact with the carbon anode, consists of larger diameter stubs. These have a thicker sheath, which serves to distribute the current across the interface and to act as a thermal insulator. This is to control the amount of heat extracted from the process and to protect the lower melting core from extreme temperatures, which occur when an anode is incorrectly set, or slips in the clamp. Furthermore there is a thermally insulating disc inside the stub at the bottom of the core, whose function is to further control process heat extraction. 'Dropped' anodes are known to be the main causes of anode 'burn-offs' in the process. Burn-offs occur when an anode draws a high current, well above its normal current, and generates so much heat internally that the cast iron thimble, which secures the carbon block to the assembly, melts (1100 °C) and the anode separates. The burn-offs represent a major disturbance to the process. They require unscheduled anode changes and usually result in anode assembly damage. Burn-offs in terms of their impact on cost, efficiency and worker health and safety, represent a cost to the process, which is many times that of the cost of the wasted anode and damaged anode assembly. Burn offs are best avoided.

The strategy commonly used in burn-off prevention is based on using electrical signal noise (pot noise) to detect possible existence of dropped anodes. The control system responds to this problem through a sequence of automatic responses. When this sequence is exhausted an alarm is raised and manual intervention requested. Depending on the work flow and other activities, pot operators may respond immediately, or in due course. The usual operator response is to manually check all anode assemblies in the pot in order to detect the problem anode and to action

it. If the dropped anode is detected sufficiently early, the anode can be raised and no further damage is sustained. If however the burn-off threshold of the anode is low, it usually burns off by the time the alarm is raised. Therefore to reduce the incidence of burn-offs, the problem

5 anodes must have a high burn-off threshold. The magnitude of a disturbance due to a "dropped" anode must be sufficiently large (high current draw by one anode) to be identified as a possible anode problem and such high current drawing anodes must survive under this stressed high current condition long enough, for the problem to be corrected. The
10 anode assembly of the present invention is designed to have a much higher burn-off threshold and a much higher assembly damage threshold, when compared to conventional anode assemblies.

The upper part of the assembly is constructed so that an elastic
15 deformation of the assembly accommodates the miss-match of thermal expansion between the yoke or gusset holding the anode rod and the stubs, which are embedded in the carbon blocks. As the carbon block, which has a different thermal expansion to the anode assembly, is rigidly attached to the stubs of the assembly, thermal stresses on the carbon
20 and the assembly are set up during service. In the conventional anode assembly, the yoke is of a rigid construction, usually made from cast steel, and depending on its size and operating temperature, can either cause the carbon blocks to crack or result in yielding and plastic deformation of high temperature softened, mild steel stubs. This plastic
25 deformation of the assembly increases with each cycle, leading to problems with stub toe-in. This requires the conventional anode assemblies to be periodically refurbished to re-set, or replace the stubs. The high temperature in the stubs sometimes causes them to extrude, thus over time, become longer and thinner. This also has a negative
30 impact on assembly performance and increases the anode assembly maintenance costs. Furthermore anode assemblies in which the stubs are either thinned down or miss-aligned with the anode stub-hole have higher electrical losses.

Specifically, the anode rod assembly of the present invention is preferably formed from a round rod, made of a material with a high electrical and a high thermal conductivity, inserted into a thin walled sheath of corrosion resistant material, which has a high temperature strength. Electrical grade copper is the preferred conductor material, whereas various grades of stainless steel are preferred, although mild steel or high carbon boiler tube can be used. The sheath (or in some cases the copper rod) is tapered on both ends and metallized with a brazing compound before being assembled. The assembled rod and tube are then bent into a "U" shape to make the yoke. The stubs, which receive the tapered ends of the yoke are also of tubular construction and have a receiving taper machined into them. This taper is designed to achieve compression of contact surfaces and leave a gap between the bottom of the stub and the bottom of the core. The yoke is pressed into the stubs with a very high load (>100 tonnes), which results in the compression of the joints between the core and sheath and between the sheath and stubs. The combination of pressure and taper are designed to achieve a partial expansion of the stubs. The tops of stubs are then secured to the sheath by welding. The pressed assembly is then preheated in a furnace and the previously sprayed brazing compound wets and spreads over all contact surfaces and thus, under capillary action, achieves filling and sealing of any interfacial gaps. This creates an excellent electrical contact and achieves the exclusion of oxygen from contact surfaces. A metal plug is machined to close the bottom of the stub. An insulating disc made of compressed ceramic fibre insulation is placed into the space between the core and the metal plug and the stub bottom is sealed by circumferential welding of the plug to the stub.

A deep groove is milled in the top of the yoke. This groove is designed to reduce the rigidity of the yoke and to receive two anode stems for welding. The main anode stem is designed to be clamped into the existing anode clamps and fit into the existing anode handling equipment. The auxiliary stem is shorter and extends from below the clamps to the yoke. The auxiliary stem is welded to the main stem at its top and to the yoke at its bottom. This structure, with a deep groove and

dual rod construction, is elastic. It is capable of flexing to accommodate any miss match in thermal expansion between the assembly and the carbon block, without resulting in permanent deformation. The structure, in the present form however, would be structurally weak. The mechanical strength and toughness in the assembly is achieved by slipping a flared stainless steel collar over the dual stems and welding the collar to the sheath of the yoke. The collar allows a certain degree of flexing in the yoke, but resists plastic deformation. The collar is attached to the conductive anode stems by mechanical indentation and welding.

10 Mechanical indentation provides a mechanical anchorage of the assembly in case of weld failure and at the same time reduces stress on welds to reduce the likelihood of such failure. The welding seals the yoke and excludes the possibility of oxygen ingress from the top.

15 As the carbon anode is progressively consumed during electrolysis, the top and the sides of the anode are also partially consumed by air ingress under the ore cover and by CO_2 gas released during electrolysis. This non-electrolytic consumption of carbon not only increases the anode consumption, but also exposes the stubs to a possible exposure to
20 molten bath. In some cases, as the anodes reach the end of their useful life and the cell has a high bath height, the anode butt can become completely submerged below the surface of the bath. In this case the top part of stubs become exposed to the molten bath and can be easily attacked by bath. The progressive dissolution of stubs damages the
25 anode assembly, thus requiring costly maintenance and at the same time contaminates the metal produced with iron. Although the raw materials typically used in the production of aluminium contain less than 100 ppm of iron, a typical smelter produces aluminium metal with an iron content between 0.1 and 0.2 wt. %. Most of this iron comes from anode
30 assemblies either via formation of scale, which separates and mixes with the recycled bath or via flux wash (dissolution attack) of anode stubs.

The thermal and heat generation properties of the present assembly are adjusted to exclude the possibility of flux wash even under the conditions
35 of fully submerged anode operation. The heat extraction through the

highly conductive core cools the top of the anode which reduces the amount of airburn and the possibility of stub exposure to a molten bath. Furthermore the heat extraction cools the exposed stubs to a temperature which ensures that even if the stubs were completely submerged below the surface of molten bath a frozen cryolite ledge would form on the exposed surfaces and prevent flux wash.

Because of the latter construction, should the anode assembly become damaged, by some extreme circumstances, the anode assembly could not be repaired without the use of specialised equipment and for this reason would be best returned to the specialist manufacturer for refurbishment and/or recycling. The emphasis of this design is prevention of damage (process indestructibility), rather than ease of repair.

Brief Description of the Drawings

FIG. 1 is a schematic sectional view taken through a Hall-Heroult smelting cell and illustrates the anode assembly of the present invention formed by bending of a tubular composite in the shape of an inverted "U". Larger diameter stubs are attached to the two legs of the "U". An anode stem widened at its bottom rises from the yoke to the anode ring bus. The widened part of the anode rod is fully encased in a stainless steel collar consisting of a flared square hollow section, which is welded to the yoke and to the anode stem.

FIG. 2 is an exploded view of the anode assembly elements which when joined together make up the assembly.

FIG. 3 is a detailed view of the tapered stainless steel sheath and of the corresponding tapered hole in the stub which show how the stub is assembled to achieve compression of contact surfaces.

FIG. 4 is a cross sectional view of the dual stem arrangement and the 'in-built' yoke flexing mechanism consisting of a deep groove in the yoke and a flared square hollow section.

FIG. 5 is an output from a thermoelectric model showing a typical temperature distribution in a conventional anode assembly under submerged conditions.

- 5 FIG. 6 is an output from a thermoelectric model showing a typical temperature distribution in an anode assembly of present invention under submerged conditions.

10 TABLE 1 is a summary of output from thermoelectric and reaction modeling of anodes showing predicted thermal, electric and reactivity performance of various anode assembly designs.

15 TABLE 2 is a summary of output from thermoelectric modeling of various anode assembly designs showing their propensity for damage by flux wash under submerged conditions.

20 TABLE 3 is a summary of output from thermoelectric modeling of various anode assembly designs showing their threshold for anode burn off and assembly damage.

Description of the Preferred Embodiments

25 An aluminium reduction cell used for commercial production of aluminium is illustrated in FIG.1 of the drawing and is designated by reference numeral 10.

30 The electrolytic cell 10 is defined by an exterior shell 11 lined internally with insulation 12. A cathode collector bar 13 is connected to the cathode bus bar 14 (negative source of power) and embedded in cathode block 15. Molten aluminium A is contained within the walls of the cell 16 covered by frozen cryolite ledge L. In the molten electrolyte E and within which at least partly immersed and suspended from above a one or more carbon blocks C which are attached to the anode assemblies 17 of the present invention. Solidified alumina and cryolite S cover the anodes C
35 and form a crust. The anode assemblies are connected to the anode ring

bus 18 (positive source of power) via anode clamps 19. The steel shell 11 is of the electrolytic cell 10 is covered by conventional gas collection hood H.

5 Electricity is conducted to the carbon block C by a novel anode assembly of the present invention which is generally designated by the reference numeral 17 and specifically adapted for use during the production of aluminium via the Hall-Heroult process.

10 The anode assembly includes the main anode rod 20, which is usually made of copper or aluminium and generally has rectangular configuration as can be seen in FIG. 2. This main rod is attached to the "U" shaped yoke 21. The yoke supports two hollow stubs 22 which contain an insulating disc 23 and are sealed on the bottom by a welded plug 24. The ends of
15 the yoke are slightly tapered and metallized with a brazing compound 25. The yoke is placed into a special pressing jig (not shown) and pressed into the stubs to cause their partial expansion. A deep welding groove 26 is milled into the top of the yoke to take the main anode rod 20 and the auxiliary anode rod 27. Both rods are covered by a stainless
20 steel collar which is flared at its bottom and welded to the yoke and to the rods.

Details of electrical and mechanical connection between the yoke and stub is shown in FIG 3. The electrical connection between the steel stub
25 and the electrically conductive core of the yoke 29 occurs via a tapered pressure fit between the stainless steel sheath 30 and the machined tapered hole in the stub 31. The mechanical connection between the steel stub and the yoke is made via a weld 32. To enhance the electrical connection and to reduce the friction during pressing operation the outer
30 surface of the tapered part of the yoke is metallized with a brazing compound. This on subsequent heat treatment melts and reacts with the mating surfaces thus enhancing the electrical connection and excluding the possibility of contact deterioration due to oxygen ingress. The separation of mechanical and electrical functions ensures that the weld
35 on top the stub is not weakened by passage of current and generation of

heat. Similarly any deterioration of the quality of the welded joint will not result in deterioration of electrical performance of the assembly. The reduced perimeter area of the arms of the yoke combined with the highly conductive core impart cooling to the top of the stub which enables it to operate in bath under submerged conditions without suffering from stub wash.

Details of the rod to yoke connection are illustrated in FIG 4. The main anode rod 20 is first beveled for welding and inserted into the milled grove 26 on top of the yoke. The main rod is then welded to the yoke on both sides with a full penetration fillet weld 33. This is followed by insertion and welding of the auxiliary rod 27, which is welded only on one side. A specially fitting and flared stainless steel collar is slipped over both rods and welded to the stainless steel sheath of the yoke and the top of the auxiliary rod 35. The auxiliary rod is welded to the main rod with a full penetration fillet weld 36. The dual rod construction and the weakened structure of the yoke due to presence of a deep grove, combined with the flared stainless steel collar provide for inward flexing of the arms of the yoke without leading to permanent deformation. This flexing absorbs the miss-match of thermal expansion between the yoke and anode carbon without placing undue stress on the block.

Thermoelectric modeling results shown in FIG 5 illustrate that if a conventional anode assembly was to be operated such that the anode was under submerged under molten bath the stub would be attacked. It shows that with molten bath E flooding over the top of the carbon C, the stub 22 would reach a temperature at the point of exposure 37 which is above the melting point of the bath (955 °C). Stub attack would be inevitable.

The results of thermoelectric modeling of an anode fitted with an assembly of present invention shown in FIG 6 illustrates that if an advanced anode assembly was used to operate an anode so that it is submerged under the bath, the stub of such an assembly would not be attacked. It shows that a frozen cryolite ledge L would form on the carbon

anode C which surrounds the stub 22 which would protect the stub from any attack. The maximum temperature to which a stub attached to an assembly of present invention could possibly reach under such conditions is 825 °C, which is over 100 °C below the melting point of bath E.

5 TABLE 1 Shows the summary of thermoelectric and reaction modeling which shows that the anode assemblies of the present invention have the capacity to reduce the maximum service temperature of the critical components of the assembly by 100 to 200 °C. This reduces the heat
10 stress and chemical damage an assembly is likely to suffer during normal operations. It also shows that the maximum anode top temperature could be reduced from present 800 °C to less than 650 °C. This reduction in temperature would reduce carbon consumption by more than 10 % by virtually eliminating all redundant carbon consumption. The results also
15 predict that an anode fitted with an anode assembly of present invention would have a much lower electrical voltage loss (2 kW cf. 2.8 kW) and a much greater process heat extraction capability (4.2 vs 2.4 kW). This means that the production of aluminium could be made more efficient due to reduced electrical losses and the production process could be
20 intensified as the anode assembly had additional capacity to dissipate process heat. Also shown are the comparable modeling results obtained by modeling a copper cored anode assembly described in US 5538 607. Although the anode assemblies of the present invention have a superior performance in all respects, the assemblies could be treated as having
25 equivalent performance.

Table 2 shows the summary of results of thermoelectric modeling which shows that only the anode assemblies of the present invention have the capacity to operate in submerged mode of operation. The modeling
30 results predict that the conventional anode assemblies if submerged under liquid bath would suffer stub wash if the bath operating temperature of the cell was more than 10 °C above its liquidus temperature. As most cells operate with a superheat approaching 15 °C, this means that the conventional anode assemblies are not operated
35 under submerged conditions. In cases where it happens by accident or as

a result of excessive carbon airburn leading to exposure of stubs, the anode assemblies become damaged and require costly stub replacement. The results further show that the stubs of the invention described in US 5538 607 would also suffer from stub wash if the stubs were exposed to molten bath with bath superheat above 13 °C. Indeed, the invention claims novelty in the ability to repair damaged legs of the assembly.

"Because of the construction, should the ring and or the end of the leg (stub) eventually be consumed to a point at which power efficiency transfer is undesirably diminished, the carbon block is removed, any consumed portion of the ring and/or lower end portion of the sleeve and/or lower end portion of the leg is removed via a cutting torch for example, and a fresh end of the leg is exposed. Another metal ring having polygonal opening corresponding to the exterior polygonal configuration of the "fresh" leg is slipped upon the latter, rewelding both axially and circumferentially."

The modeling however predicts that the minimum superheat required to cause stub wash on the anode assembly of the present invention is above 25 °C. Since such high superheat during normal cell operations is very rare, this demonstrates that the anode assemblies of the present invention are unlikely to suffer damaged as a result of normal process excursions.

Table 3 shows the results of thermoelectric modeling of the most stressful condition which may exist in an aluminium reduction cell. This occurs when an anode burn-off occurs. The modeling results predict that a conventional anode would burn off its normal current loading was increased by 50 %. At that point the average stub temperature would be well above the melting point of bath, therefore a burn off would most probably lead to anode assembly damage. The result for copper cored anode assembly described by invention US 5538 607 show that this anode assembly has a greater burn off threshold compared to conventional anode assembly (13.9 vs 8.4 KA), but it too would suffer from stub damage if the stub came into contact with molten bath. The critical superheat for stub wash was only 9 °C. The results of modeling for the anode assemblies of the present invention, show that the burn-off

threshold is much higher (14 to 18 kA cf. 8.4 kA). The critical superheat for stub wash is also predicted to remain above 20 °C. This suggests that the anode assembly of the present invention, due to the specificity of its construction, would resist damage even under the most stressful of situations.

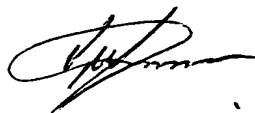
The object of this invention was the creation of a high performance, low maintenance anode assembly suitable for use in aluminium reduction cells. The high electrical and thermal performance was achieved through use of highly conductive core inside a protective sheath and the use of totally sealed design which excludes possibility for oxygen penetration of contact surfaces. Further the electrical performance was enhanced through use of high pressure contacts and brazed joints.

Low maintenance was achieved by encasing all hot components of the assembly in a heat and chemically resistant stainless steel. Further, its mechanical robustness was enhanced through separation of the electrical and mechanical functions of the assembly such that mechanical joints are not additionally stressed by heat generated by passage of current and electrical joints do not suffer as a result of mechanical failure.

The innovative use of ceramic fibre insulation in the stub had an additional benefit when it was accidentally discovered that the burn off threshold of the anode assembly was increased despite reduced heat losses.

Claims

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FIG. 1.

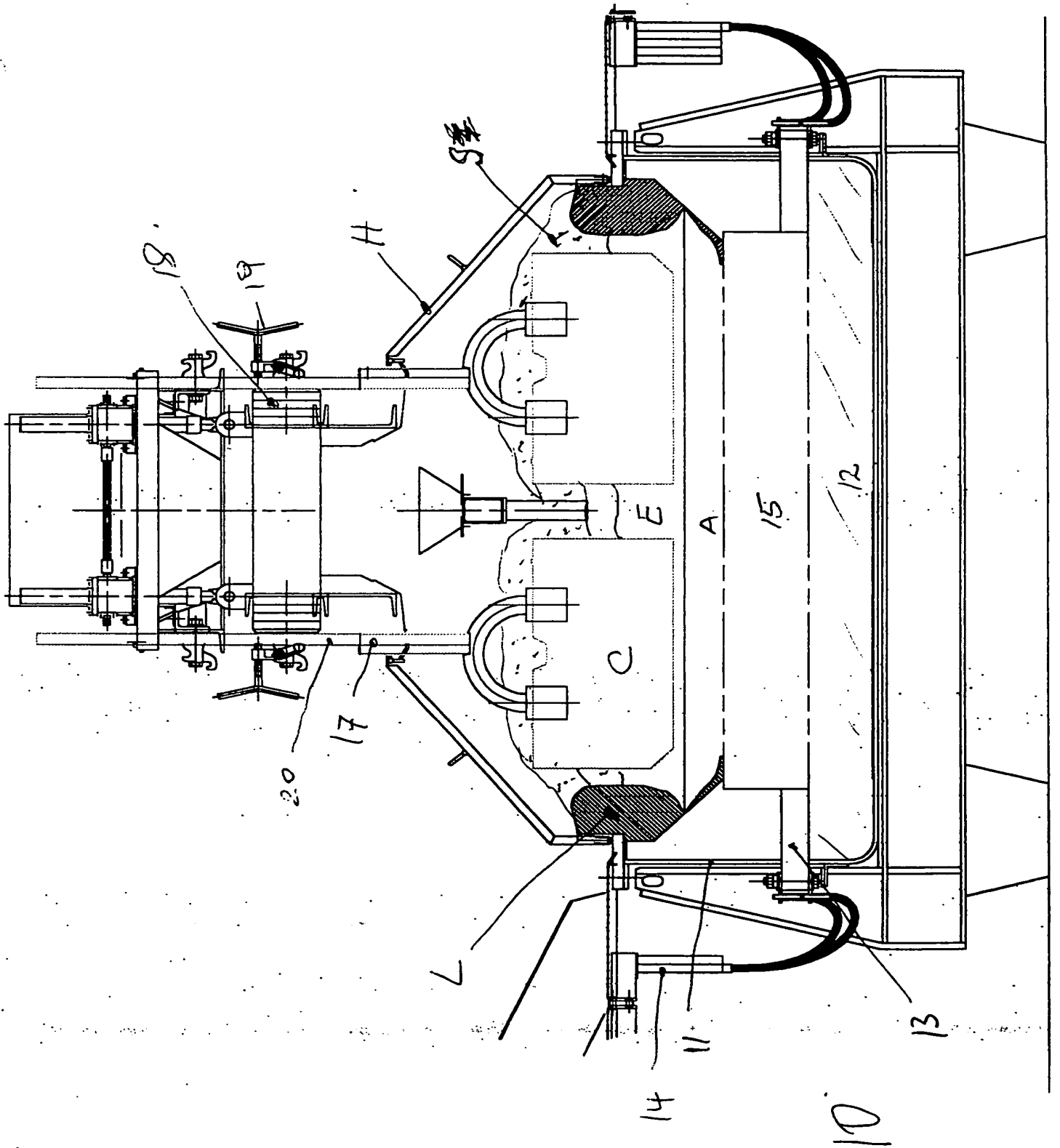


Fig 2

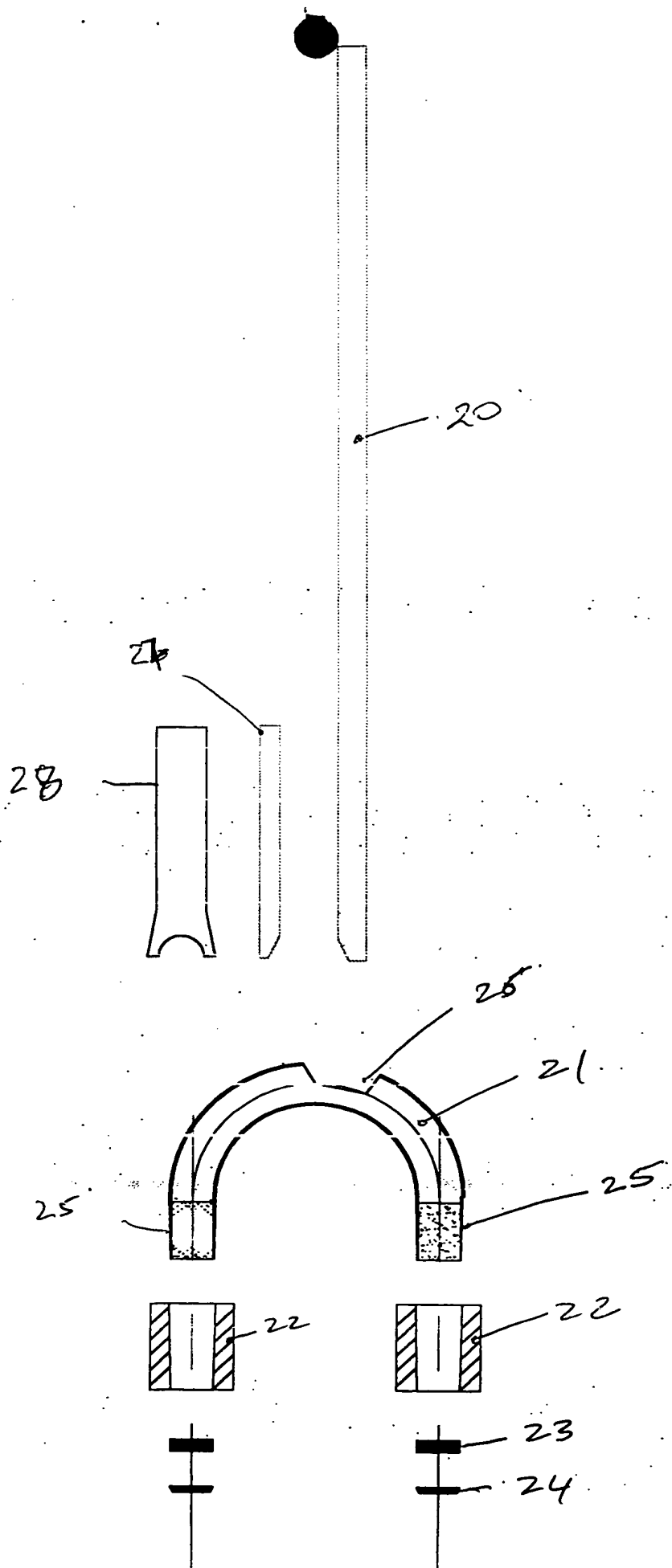
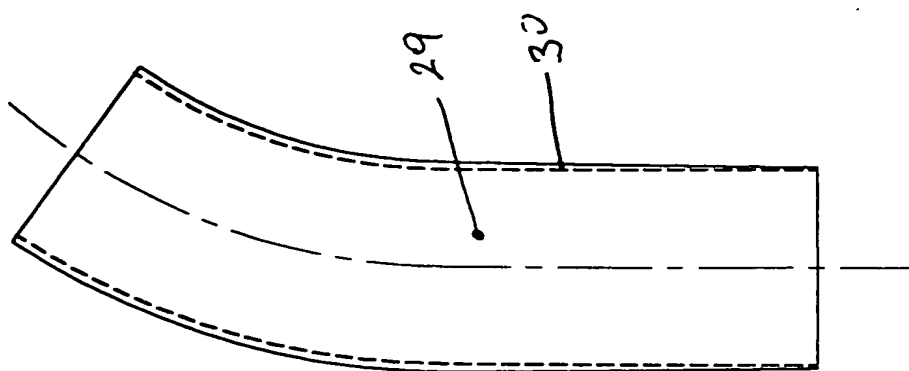
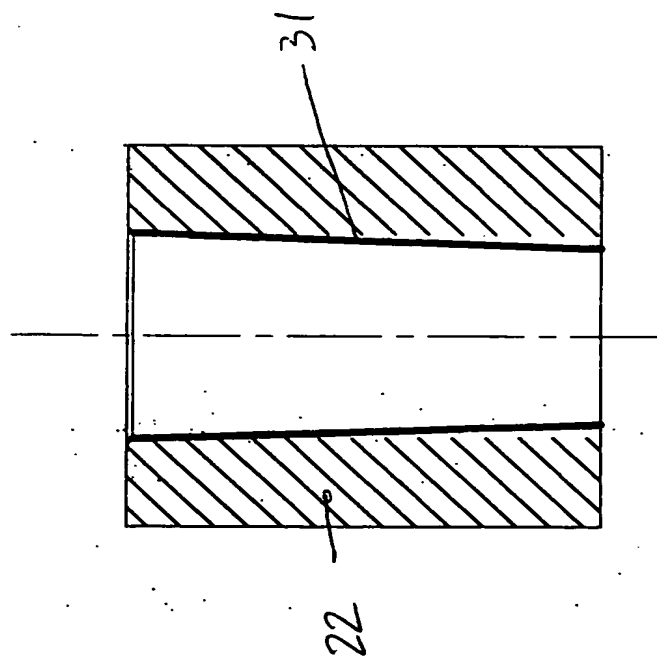
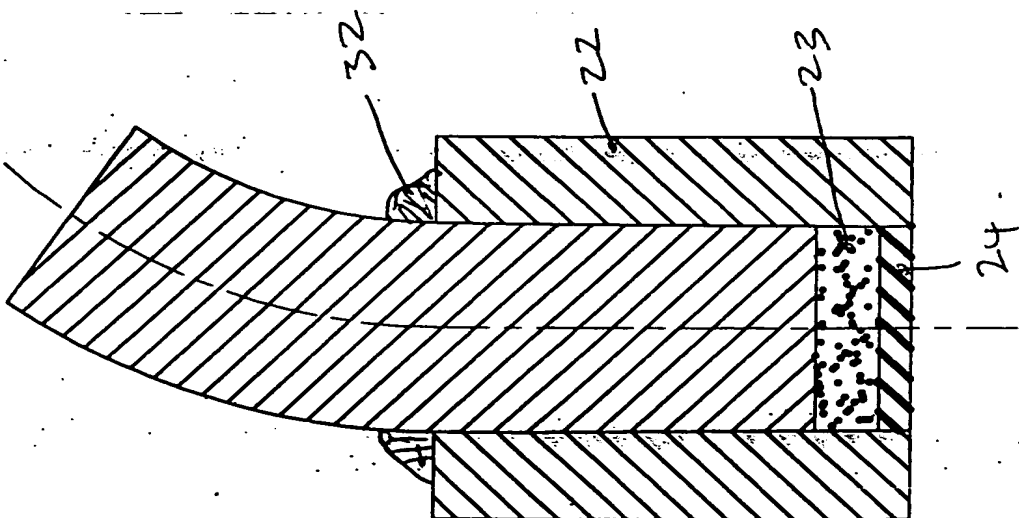


FIG 3



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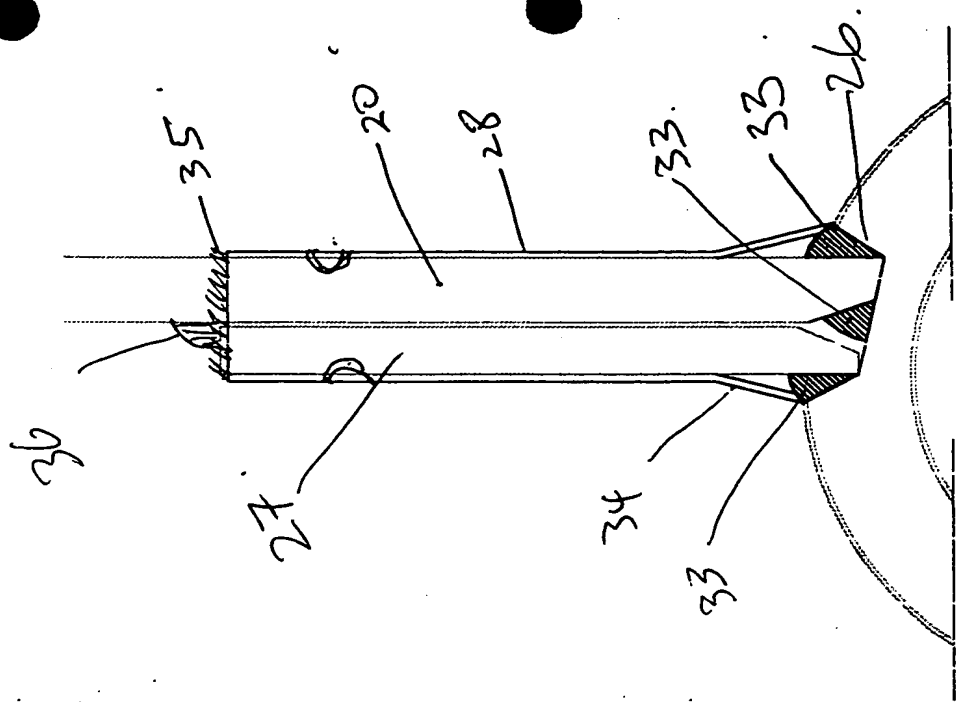
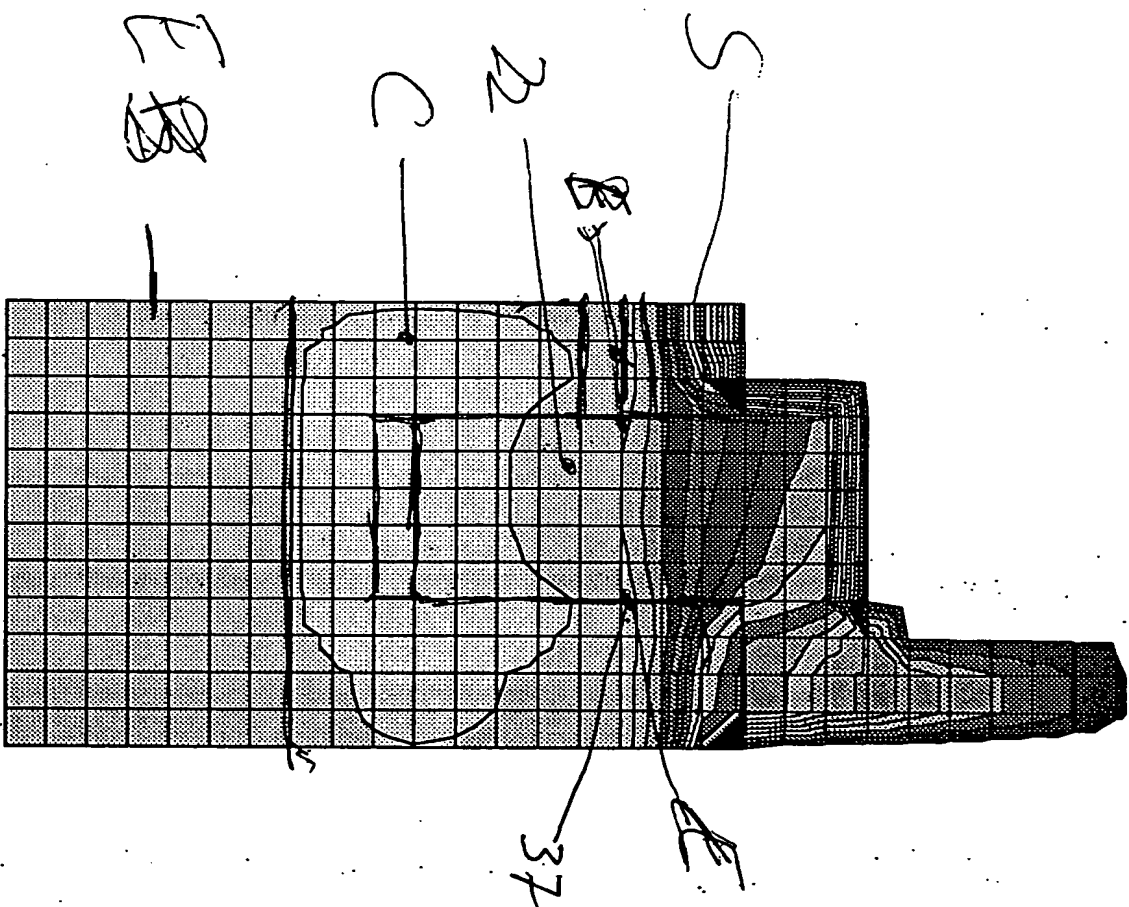
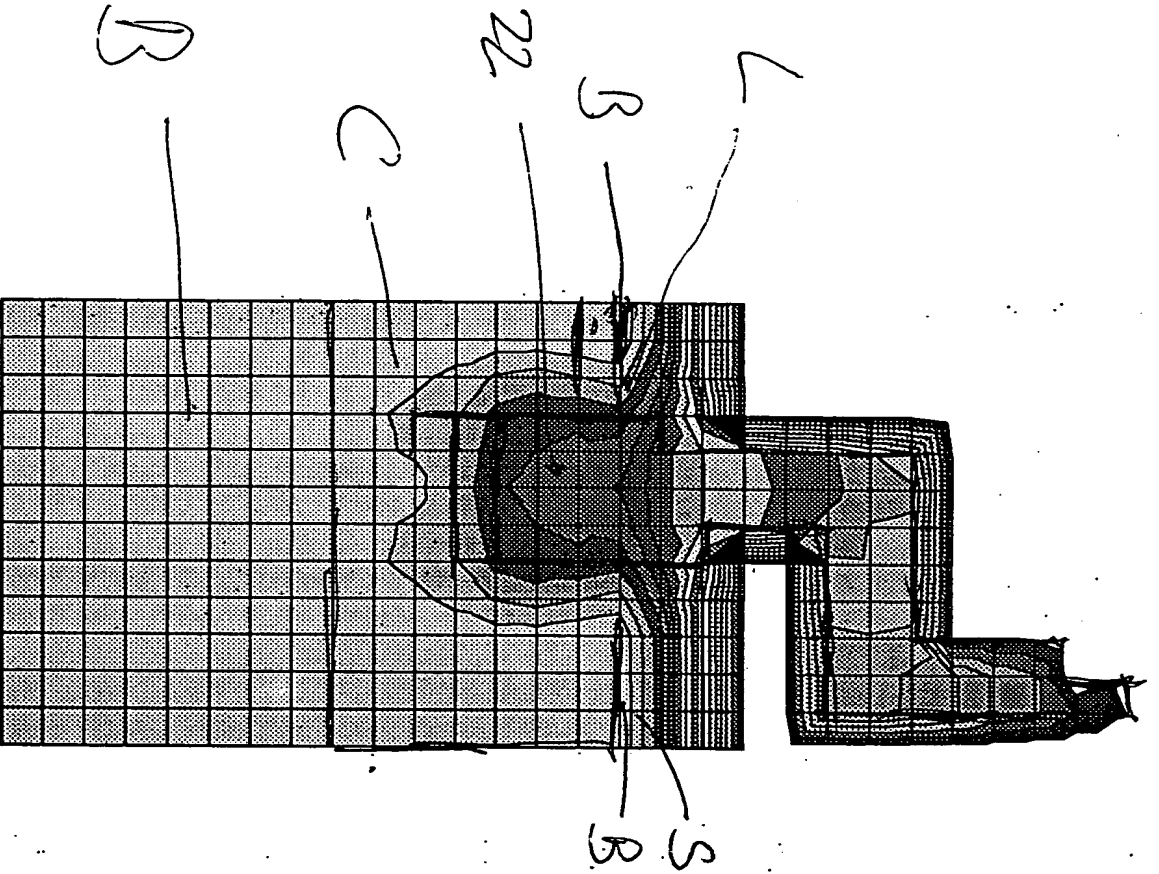


FIG 5



975-1025
925-975
875-925
825-875
775-825
725-775
675-725
625-675
575-625
525-575
475-525
425-475
375-425
325-375
275-325
225-275
175-225
125-175
75-125
25-75

FIG 6



- 925-975
- 875-925
- 825-875
- 775-825
- 725-775
- 675-725
- 625-675
- 575-625
- 525-575
- 475-525
- 425-475
- 375-425
- 325-375
- 275-325
- 225-275
- 175-225
- 125-175
- 75-125
- 25-75

Table 1

Normal Operation		Existing		US 5538 607	Present invention		
				70 mm	70 mm ins	90 mm ins	90 mm unins.
Anode Amperage	kA	5.1	6	6	6	6	6
Max Anode rod Temp	°C	311	323	250	231	216	230
Gusset Temp	°C	397	443	267	248	230	245
Ave Stub Temp	°C	752	808	552	542	476	463
Max Cu/Stub Temp	°C	808	868	539	496	420	477
Anode Top Temp	°C	789	839	690	663	627	619
Anode resistance	micro.ohm	78.0	77.7	65.1	59.8	53.7	53.1
Net Carbon	kgC/kgAl	0.463	0.490	0.421	0.412	0.403	0.401
Anode Power Loss	kW	2.0	2.8	2.3	2.0	1.9	1.9
Anode HeatExtraction	kW	2.4	2.6	3.6	3.4	3.8	4.2

Table 2

Submarine		Existing		US 5538 607	Present invention		
				70 mm	70 mm ins	90 mm ins	90 mm unins.
Max Anode rod Temp	°C	339	346	318	320	393	392
Gusset Temp	°C	476	485	344	349	428	428
Ave Stub Temp	°C	963	971	814	883	890	885
Max Cu/Stub Temp	°C	985	997	751	862	868	892
Equivalent Heat Loss	kW	3.7	3.7	5.8	6.3	8	8
Max wash superheat	°C	11.1	10.1	13.4	25.6	27.4	26.2

Table 3

Burn off		Existing		US 5538 607	Present invention		
				70 mm	70 mm ins	90 mm ins	90 mm unins.
Amperage	kA	8.4		13.9	14.0	18.1	15.6
Ave Stub Temp	°C	1009		928	952	962	932
Max Cu Temp	°C	1048		917	924	929	958
Max wash superheat	°C	3.1		9.0	20.6	23.5	23.2
Max Anode Rod Temp	°C	505		366	343	390	387
Gusset Temp	°C	610		394	362	421	419

